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# GLOBAL $L^2$ -BOUNDEDNESS THEOREMS FOR A CLASS OF FOURIER INTEGRAL OPERATORS AND THEIR APPLICATION (Recent Trends in Microlocal Analysis)

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# GLOBAL $L^2$ -BOUNDEDNESS THEOREMS FOR A CLASS OF FOURIER INTEGRAL OPERATORS AND THEIR APPLICATION

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This article is based on the joint work with Michael Ruzhansky (Imperial College) which will appear in [13], [14], [15] and so on.

## Fourier integral operators

We consider the following Fourier integral operator:

$$(1) \quad Tu(x) = \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} e^{i\phi(x,y,\xi)} a(x,y,\xi) u(y) dy d\xi$$

( $x \in \mathbb{R}^n$ ), where  $a(x,y,\xi)$  is an amplitude function and  $\phi(x,y,\xi)$  is a real phase function of the form

$$\phi(x,y,\xi) = x \cdot \xi + \varphi(y,\xi).$$

Note that, by the equivalence of phase function theorem, Fourier integral operators with the local graph condition can always be written in this form locally.

Local  $L^2$  mapping property of (1) has been established by Hörmander [9] and Eskin [7]. The aim of this article is to present *global*  $L^2$ -boundedness properties of operators (1).

## When is $T$ globally $L^2$ -bounded?

• (Asada and Fujiwara [1]) Assume that all the derivatives of  $a(x,y,\xi)$  and all the derivatives of each entry of the matrix

$$D(\phi) = \begin{pmatrix} \partial_x \partial_y \phi & \partial_x \partial_\xi \phi \\ \partial_\xi \partial_y \phi & \partial_\xi \partial_\xi \phi \end{pmatrix}$$

are bounded. Also assume that  $|\det D(\phi)| \geq C > 0$ . Then  $T$  is  $L^2(\mathbb{R}^n)$ -bounded.

This result was used to construct the fundamental solution of Schrödinger equation in the way of Feynman's path integral.

(The result of Kumano-go [12] was used to construct the fundamental solution of hyperbolic equations, and it requires that

$$J(y,\xi) = \phi(x,y,\xi) - (x-y) \cdot \xi$$

satisfies

$$\left| \partial_y^\alpha \partial_\xi^\beta J(y,\xi) \right| \leq C_{\alpha\beta} (1 + |\xi|)^{1-|\beta|}$$

for all  $\alpha$  and  $\beta$ .)

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However, there one had to make a quite restrictive and not always natural assumption on the boundedness of  $\partial_\xi \partial_\xi \phi$ , which fails in many important cases.

The case we have in mind is

$$(2) \quad \phi(x, y, \xi) = x \cdot \xi - y \cdot \psi(\xi),$$

where  $\psi(\xi)$  is a smooth function of growth order 1. If we take  $\psi(\xi) = \xi$ , then we have  $\phi(x, y, \xi) = x \cdot \xi - y \cdot \xi$ , and the operator  $T$  defined by it is a pseudo-differential operator.

We cannot use Asada-Fujiwara's result with our example (2), because the boundedness of the entries of  $\partial_\xi \partial_\xi \phi$  fails generally. (We cannot use Kumano-go's either by the same reason.)

### Why is the phase function (2) important?

Because it is used to represent a canonical transformations. In fact, if we take  $a(x, y, \xi) = 1$ , we have

$$(3) \quad Tu(x) = F^{-1}[(Fu)(\psi(\xi))](x)$$

hence

$$T \cdot \sigma(D) = (\sigma \circ \psi)(D) \cdot T.$$

Especially, for a positive and homogeneous function  $p(\xi) \in C^\infty(\mathbb{R}^n \setminus 0)$  of degree 1, we have the relation

$$(4) \quad T \cdot (-\Delta) \cdot T^{-1} = p(D)^2$$

if we take

$$(5) \quad \psi(\xi) = p(\xi) \frac{\nabla p(\xi)}{|\nabla p(\xi)|}$$

and assume that the hypersurface

$$\Sigma = \{\xi; p(\xi) = 1\}$$

has non-vanishing Gaussian curvature.

The curvature condition on  $\Sigma$  means that the Gauss map

$$\frac{\nabla p}{|\nabla p|} : \Sigma \rightarrow S^{n-1}$$

is a global diffeomorphism and its Jacobian never vanishes. (See Kobayashi and Nomizu [11].) Hence, we can construct the inverse  $C^\infty$ -map  $\psi^{-1}(\xi)$  of  $\psi(\xi)$  defined by (5). On account of (3), the inverse  $T^{-1}$  can be given by replacing  $\psi$  by  $\psi^{-1}$ .

The  $L^2$ -property of the Laplacian  $-\Delta$  is well known in various situations. Our objective is to know the  $L^2$ -property of the operator  $T$ , so that we can extract the  $L^2$ -property of the operator  $p(D)^2$  from that of the Laplacian.

### Main result

The following is our main result, which is expected to have many applications. For  $m \in \mathbb{R}$ , we set

$$\langle x \rangle^m = (1 + |x|^2)^{m/2}.$$

Let  $L_m^2(\mathbb{R}^n)$  be the set of functions  $f$  such that the norm

$$\|f\|_{L_m^2(\mathbb{R}^n)} = \left( \int_{\mathbb{R}^n} |\langle x \rangle^m f(x)|^2 dx \right)^{1/2}$$

is finite.

**Theorem 1.** Let  $\phi(x, y, \xi) = x \cdot \xi + \varphi(y, \xi)$ . Assume that

$$|\det \partial_y \partial_\xi \varphi(y, \xi)| \geq C > 0,$$

and all the derivatives of entries of  $\partial_y \partial_\xi \varphi$  are bounded. Also assume that

$$|\partial_\xi^\alpha \varphi(y, \xi)| \leq C_\alpha \langle y \rangle \quad \text{for all } |\alpha| \geq 1,$$

$$|\partial_x^\alpha \partial_y^\beta \partial_\xi^\gamma a(x, y, \xi)| \leq C_{\alpha\beta\gamma} \langle x \rangle^{-|\alpha|}$$

for all  $\alpha, \beta$ , and  $\gamma$ . Then  $T$  is bounded on  $L_m^2(\mathbb{R}^n)$  for any  $m \in \mathbb{R}$ .

Theorem 1 says that, if amplitude functions  $a(x, y, \xi)$  have some decaying properties with respect to  $x$ , we do not need the boundedness of  $\partial_\xi \partial_\xi \phi$  for the  $L^2$ -boundedness, as required in Asada-Fujiwara [1], and we can have weighted estimates, as well.

The same is true when both phase and amplitude functions have some decaying properties with respect to  $y$ .

**Theorem 2.** Let  $\phi(x, y, \xi) = x \cdot \xi + \varphi(y, \xi)$ . Assume that

$$|\det \partial_y \partial_\xi \varphi(y, \xi)| \geq C > 0.$$

Also assume that

$$|\partial_y^\alpha \partial_\xi^\beta \varphi(y, \xi)| \leq C_\alpha \langle y \rangle^{1-|\alpha|} \quad \text{for all } \alpha, |\beta| \geq 1,$$

$$|\partial_x^\alpha \partial_y^\beta \partial_\xi^\gamma a(x, y, \xi)| \leq C_{\alpha\beta\gamma} \langle y \rangle^{-|\beta|}$$

for all  $\alpha, \beta$ , and  $\gamma$ . Then  $T$  is bounded on  $L_m^2(\mathbb{R}^n)$  for any  $m \in \mathbb{R}$ .

If the amplitude  $a(x, y, \xi)$  is independent of the variable  $x$  or  $y$ , the decaying property can be automatically satisfied. Furthermore, we can reduce the regularity assumptions for amplitude and phase functions in this case.

**Theorem 3.** Let  $\phi(x, y, \xi) = x \cdot \xi + \varphi(y, \xi)$  and  $a(x, y, \xi) = a(x, \xi)$ . Assume that

$$|\det \partial_y \partial_\xi \varphi(y, \xi)| \geq C > 0$$

and each entry  $h(y, \xi)$  of  $\partial_y \partial_\xi \varphi(y, \xi)$  satisfies

$$|\partial_y^\alpha h(y, \xi)| \leq C_\alpha, \quad \left| \partial_\xi^\beta h(y, \xi) \right| \leq C_\beta$$

for  $|\alpha|, |\beta| \leq 2n + 1$ . Also assume

$$\partial_x^\alpha \partial_\xi^\beta a(x, \xi) \in L^\infty(\mathbb{R}_x^n \times \mathbb{R}_\xi^n)$$

for one of the followings:

- (i)  $\alpha, \beta \in \{0, 1\}^n$ , (ii)  $|\alpha|, |\beta| \leq [n/2] + 1$ ,  
 (iii)  $|\alpha| \leq [n/2] + 1, \beta \in \{0, 1\}^n$ , (iv)  $\alpha \in \{0, 1\}^n, |\beta| \leq [n/2] + 1$ .

Then  $T$  is  $L^2(\mathbb{R}^n)$ -bounded.

Theorem 3 with  $\varphi(y, \xi) = -y \cdot \xi$  is a refined version of known results on the  $L^2$ -boundedness of pseudo-differential operators with non-regular symbols: (i) with  $\alpha, \beta \in \{0, 1, 2, 3\}^n$  is due to Calderón and Vaillancourt [3], (ii) is due to Cordes [6], and conditions (iii) with  $|\alpha| \leq [n/2] + 1, \beta \in \{0, 1, 2\}^n$ , is due to Coifman and Meyer [5].

**Theorem 4.** Let  $\phi(x, y, \xi) = x \cdot \xi + \varphi(y, \xi)$  and  $a(x, y, \xi) = a(y, \xi)$ . Assume that

$$|\partial_y^\alpha \partial_\xi^\beta a(y, \xi)| \leq C_{\alpha\beta},$$

for  $|\alpha|, |\beta| \leq 2n + 1$ . Also assume that

$$|\det \partial_y \partial_\xi \varphi(y, \xi)| \geq C > 0$$

and each entry  $h(y, \xi)$  of  $\partial_y \partial_\xi \varphi(y, \xi)$  satisfies

$$|\partial_y^\alpha h(y, \xi)| \leq C_\alpha, \quad |\partial_\xi^\beta h(y, \xi)| \leq C_\beta$$

for  $|\alpha|, |\beta| \leq 2n + 1$ . Then the operator  $T$  is  $L^2(\mathbb{R}^n)$ -bounded.

### An example of how to use our results

Kato and Yajima [10] showed that the classical Schrödinger equation

$$\begin{cases} (i\partial_t + \Delta_x)u(t, x) = 0, \\ u(0, x) = g(x) \end{cases}$$

has the global smoothing estimate

$$(6) \quad \|\langle x \rangle^{-1} \langle D \rangle^{1/2} u\|_{L^2(\mathbb{R}_t \times \mathbb{R}_x^n)} \leq C \|g\|_{L^2(\mathbb{R}_x^n)},$$

where  $n \geq 3$ .

From this fact, we can extract a similar estimate for generalized Schrödinger equations

$$(7) \quad \begin{cases} (i\partial_t - p(D)^2)u(t, x) = 0, \\ u(0, x) = g(x). \end{cases}$$

• **Assumption.**  $p(\xi) \in C^\infty(\mathbb{R}^n \setminus 0)$  is homogeneous of order 1,  $p(\xi) > 0$ , and the hypersurface  $\Sigma = \{\xi; p(\xi) = 1\}$  has non-vanishing Gaussian curvature.

Remember that we have the relation

$$T^{-1} \cdot p(D)^2 = (-\Delta) \cdot T^{-1}$$

by (4). Operating  $T^{-1}$  from the left hand side of equation (7), we have, by this relation,

$$\begin{cases} (i\partial_t - \Delta)T^{-1}u(t, x) = 0, \\ T^{-1}u(0, x) = T^{-1}g(x). \end{cases}$$

Hence, from (6) and Theorem 1, we obtain the following conclusion:

**Theorem 5.** Suppose  $n \geq 3$ . Under the assumption above, the solution  $u(t, x)$  to generalized Schrödinger equation (7) has the same global smoothing estimate (6) as the classical one has.

*Remark 1.* Walther [16] consider the case of radially symmetric  $p(\xi)^2$ . Theorem 5 says that we can treat more general case.

### Smoothing effect with a structure

By using the idea above, we can have more refined global smoothing estimates. In order to state them, we introduce some notations:

- Classical orbit determined by  $p(D)^2$ :

$$(8) \quad \begin{cases} \dot{x}(t) = \nabla_{\xi} p^2(\xi(t)), & \dot{\xi}(t) = 0 \\ x(0) = 0, & \xi(0) = k. \end{cases}$$

- The set of the path of all classical orbits:

$$\begin{aligned} \Gamma_p &= \{(x(t), \xi(t)); \text{sol. of (8), } t \geq 0, k \in \mathbb{R}^n \setminus 0\} \\ &= \{(t\nabla p(\xi), \xi); \xi \in \mathbb{R}^n \setminus 0, t > 0\}. \end{aligned}$$

- Notation:

$$\begin{aligned} \sigma(x, \xi) &\sim \langle x \rangle^a |\xi|^b \\ \iff & \begin{cases} \sigma(x, \xi) \in C^\infty(\mathbb{R}_x^n \times (\mathbb{R}_\xi^n \setminus 0)), \\ \sigma(\lambda x, \xi) = \lambda^a \sigma(x, \xi); (\lambda > 1, |x| \gg 1), \\ \sigma(x, \lambda \xi) = \lambda^b \sigma(x, \xi); (\lambda > 0). \end{cases} \end{aligned}$$

**Theorem 6.** Suppose  $n \geq 2$ . Assume

$$\sigma(x, \xi) = 0 \text{ on } \Gamma_p, \quad \sigma(x, \xi) \sim \langle x \rangle^{-1/2} |\xi|^{1/2}.$$

Then the solution  $u$  to equation (7) satisfies

$$\|\sigma(X, D)u\|_{L^2(\mathbb{R}_t \times \mathbb{R}_x^n)} \leq C \|g\|_{L^2(\mathbb{R}_\xi^n)}.$$

*Remark 2.* Without the structure condition  $\sigma(x, \xi) = 0$  on  $\Gamma_p$ , we have the estimate in Theorem 6 for the followings:

$$\sigma(x, \xi) = \langle x \rangle^{-s} |\xi|^{1/2} \quad (s > 1/2) \quad (\text{Ben-Artzi and Klainerman [2]})$$

$$\sigma(x, \xi) = |x|^{\alpha-1} |\xi|^\alpha \quad (0 < \alpha < 1/2) \quad (\text{Kato and Yajima [10]})$$

We have a similar result for inhomogeneous equations

$$(9) \quad \begin{cases} (i\partial_t - p(D)^2) u(t, x) = f(t, x) \\ u(0, x) = 0. \end{cases}$$

**Theorem 7.** Suppose  $n \geq 2$ . Assume

$$\sigma(x, \xi) \geq 0, \quad \sigma(x, \xi) = 0 \text{ on } \Gamma_p$$

$$\sigma(x, \xi) \sim \langle x \rangle^{1/2} |\xi|.$$

Then the solution  $u$  to (9) satisfies the estimate

$$\begin{aligned} & \|\sigma(X, D_x)u\|_{L^2(\mathbb{R}_t \times \mathbb{R}_x^n)} \\ & \leq C \left\| \langle x \rangle^{3/2} f \right\|_{L^2(\mathbb{R}_t \times \mathbb{R}_x^n)}. \end{aligned}$$

Combining Theorems 6 and 7, we have an estimate for the equation

$$(10) \quad \begin{cases} (i\partial_t - p(D)^2) u(t, x) = f(t, x) \\ u(0, x) = g(x). \end{cases}$$

**Corollary 8.** Suppose  $n \geq 2$  and  $s, \tilde{s} \geq 0$ . Assume

$$\sigma(x, \xi) \geq 0, \quad \sigma(x, \xi) = 0 \text{ on } \Gamma_p$$

$$\sigma(x, \xi) \sim |\xi|.$$

Then the solution  $u$  to (10) satisfies the estimate

$$\begin{aligned} & \left\| \langle x \rangle^{1/2} \sigma(X, D_x)u \right\|_{H_t^s(H_x^{\tilde{s}})} \\ & \leq C \left\| \langle x \rangle \langle D_x \rangle^{2s+\tilde{s}+1/2} g \right\|_{L^2(\mathbb{R}_x^n)} + C \left\| \langle x \rangle^{3/2} f \right\|_{H_t^s(H_x^{\tilde{s}})}. \end{aligned}$$

## Derivative Nonlinear Schrödinger Equation

Finally, we refer to further applications. We consider the following nonlinear Schrödinger equation:

$$(11) \quad \begin{cases} (i\partial_t + \Delta_x) u(t, x) = |\nabla u(t, x)|^N \\ u(0, x) = g(x), \quad t \in \mathbb{R}, x \in \mathbb{R}^n. \end{cases}$$

What is the condition of the initial data  $g(x)$  for equation (11) to have time global solution? There are some answers:

- $N \geq 3$  (Chihara [4]). Smooth, rapidly decay, and sufficiently small.
- $N \geq 2$  (Hayashi, Miao and Naumkin [8]).  $g \in H^{[n/2]+5}$ , rapidly decay, and sufficiently small.

**Question:** Can we weaken the smoothness assumption for  $g(x)$ ?

**Answer:** Yes if the non-linear term has a “structure”!

Instead of (11), we consider

$$(12) \quad \begin{cases} (i\partial_t - p(D)^2) u(t, x) = |\sigma(X, D_x)u|^N \\ u(0, x) = g(x), \quad t \in \mathbb{R}, x \in \mathbb{R}^n, \end{cases}$$

where

$$(13) \quad \begin{cases} \sigma(x, \xi) \geq 0, & \sigma(x, \xi) = 0 \quad \text{on } \Gamma_p, \\ \sigma(x, \xi) \sim |\xi|. \end{cases}$$

- Examples of nonlinear terms which satisfy (13) in the case  $p(D)^2 = -\Delta_x$ :

$$\sigma(x, \xi) = \left| \frac{x}{|x|} \wedge \xi \right|^2 |\xi|^{-1} \quad \text{for large } |x|$$

**Theorem 9.** Suppose  $n \geq 2$ ,  $s > (n+3)/2$ , and  $N \geq 3$ . Assume that  $\langle x \rangle \langle D_x \rangle^s g \in L^2$  and its  $L^2$ -norm is sufficiently small. Then equation (12) has a time global solution. (In the case  $N = 2$ , we need more structure.)

Key point to the proof of Theorem 9. Use Corollary 8 with  $f = |\sigma(X, D_x)u|^N$ . The space  $H_t^s(H_x^{\tilde{s}})$  is an algebra if  $s > 1/2$  and  $\tilde{s} > n/2$ . Then we have

$$\begin{aligned} \left\| \langle x \rangle^{3/2} |\sigma(X, D_x)u|^N \right\|_{H_t^s(H_x^{\tilde{s}})} &\leq \left\| \langle x \rangle^{1/(2N)+1/N} \sigma(X, D_x)u \right\|_{H_t^s(H_x^{\tilde{s}})}^N \\ &\leq \left\| \langle x \rangle^{1/2} \sigma(X, D_x)u \right\|_{H_t^s(H_x^{\tilde{s}})}^N \end{aligned}$$

if  $N \geq 3$ .



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